Dynamics of Oceanic Motions

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LONG-TERM GOALS

This research is concerned with accurate and efficient four-dimensional field estimation and fundamental dynamical process studies for the mid-latitude ocean. The research is multiscale, interdisciplinary and generic. The methods are applicable to an arbitrary region of the coastal and/or deep ocean and across the shelf-break. Results contribute to: knowledge of realistic regional processes and general physical and physical/acoustical processes; and to the formulation and initiation of studies on physical-biological-chemical interactions essential to the understanding of biogeochemical-cycles and ecosystem dynamics.

OBJECTIVES

General objectives are:
(I) To determine for the coastal and/or coupled deep ocean the multiscale processes which occur:
- I) in the physical response to external and boundary forcings and via internal dynamical processes;
- ii) in the physical-biological-chemical interactions which control productivity and provide connectivity and isolation mechanisms for (sub) regional ecosystems;
- iii) in the physical-acoustical interactions which influence acoustic propagation and tomographic inversions.

(II) To nowcast, forecast and simulate with data assimilation realistic oceanic fields with (sub) mesoscale resolution over large scale domains and to understand the essential dynamics controlling forecasts and regional predictability. Specific objectives include:
- i) Northwest Atlantic shelf seas studies with atmospheric and river flux;
- ii) Mediterranean studies in the Sicily Straits and the eastern basin;
- iii) Extension and application of our balance of terms scheme (EVA) to multiscale, interdisciplinary fields with data assimilation;
- iv) Extension and application of our hybrid ESSE data assimilation scheme to interdisciplinary fields and parameter estimation; and,
- v) Regional predictability studies.

APPROACH

Field estimates are obtained via the melding of data and dynamics in a modular, flexible forecast and simulation system (Harvard Ocean Prediction System - HOPS). Dynamically adjusted fields are used in detailed physical, acoustical and biogeochemical/ecosystem process analyses based on the balance of terms of the dynamical equations. Data assimilation is carried out for dynamical adjustment, dynamical interpolation and data-driven simulations. Assimilation algorithms include a robust "optimal" interpolation scheme and a hybrid method for evolving forecast errors based on an EOF representation

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of the dominant error subspace and an ensemble forecast error estimate (Error Subspace Statistical Estimation - ESSE). The pre-treatment of data before assimilation, via structured data models (e.g. feature models), maximizes the data information content. A sequence of two-way nested model domains and nested observational strategies are used to establish accurate representations of multi-scale processes and interactions. Theoretical, GFD, and data driven simulations are utilized with feedbacks.

WORK COMPLETED

A major synthesis of the coastal oceans of the whole earth has been completed and has appeared as two volumes of The Sea (3, 4). The table of contents and author list for a new synthesis of biological-physical interactions, which will appear as a new volume of The Sea, has been completed A substantial mathematical and conceptual review of data assimilation and its application in the coastal ocean has been published (5). An overview of the use of the Harvard Ocean Prediction System (HOPS) in the coastal ocean has been published (6) and another will be published shortly (20).

Our data assimilation and ESSE methodologies continue to be exercised and improved (22, 23). Methods for error subspace initializations, for adaptive ESSE and for smoothing via ESSE were further developed and are being published (16). ESSE was utilized in RR96, RR97, RR98 (15), as well as in recent OSSE's, adaptive sampling and data-driven physical field and error simulations for the Mass Bay Sea Trial of the LOOPS program.

The dynamical and theoretical basis for the advanced study of the Massachusetts Bay/Gulf of Maine multidisciplinary dynamics was completed within Harvard’s LOOPS/AFMIS programs. Physical and biological OSSE's were carried out prior to the September Sea Trial.

The first phase of a new general theory of advective effects on biological dynamics in the sea has been completed (7) and the second phase of this study, investigating localization, light limitation and nutrient saturation, has been completed and submitted for publication (13).

A GFD study of mesoscale-surface boundary layer (SBL) interactions has been completed (8). Evidence from data, simulations and satellite altimetry have been brought together to describe the vertical fluxes induced by the dynamics of mesoscale eddies (2, 9).

A major study, in three parts, kinematically links a set of feature models for the Gulf Stream system (10), calibrates them within the PE model against the synthesis of existing synoptical/dynamical data (11) and then verifies the predictive capability of the system (12). Results of this work have been reported previously.

Regional studies via HOPS are ongoing. Significant new results on the structure of the circulation (21) and water masses (14) of the Sicily Straits and the adjacent Ionian and Tyrrhenian Seas have been obtained and dynamical studies are underway.

A discussion of the role and opportunities for ocean acoustics in modern ocean science was given at a tribute for Dr. Ding Lee (1).

RESULTS

The completed volumes of The Sea provide a treatise available to the international which allow for the develop of analogues and principles for the coastal ocean. These can be of great utility to the community in developing and initiating coastal research. The volume on biological-physical interactions will be published in the near future. The data assimilation study contributes uniquely to overview literature because of it completeness and unique viewpoint. Overviews of the HOPS system are a method of continuing to disseminate up-to-date information on HOPs as a basis for training and new transitions.

Classical objective analyses were successfully compared to ESSE and the multivariate ESSE advantages analyzed (16). The sensitivity to the error subspace size was exemplified. The adaptive component of ESSE has been successfully utilized (15) and efficient systems for continuous minimum error variance filtering via adaptive ESSE have been obtained. The use of ESSE for continuous organization of the dominant nonlinearly evolving ocean variability has been illustrated. Several of the 3D multivariate processes responsible for the August-September period of most energetic variability in the Strait of Sicily were analyzed (15). The spreading of the Levantine Intermediate Water (LIW) was investigated using OI and ESSE. The data-driven simulations suggest that several phenomena interacting on multiple scales are responsible for the dispersal. The LIW predominantly spreads in a rotating motion along sloping isopycnals from the centers of meandering cyclonic gyres into adjacent jets and anticyclonic gyres, which further advect the intermediate water. The source of LIW in the spring is both internal mixing and surface forcing. From the assimilation point of view, a stochastic PE forcing was successfully used to model surface dynamical errors.

During the Mass. Bay Sea Trial, HOPS was utilized for field and error estimation (hindcasts, nowcasts and forecasts). The procedures included FNMOC based atmospheric forcings, multiple nested domains, nine state variable biological model, OI and ESSE data assimilation schemes, and multiscale sampling strategies adapted as a function of the field and error nowcasts and forecasts. A good overview of this work is found at http://www.deas.harvard.edu/~leslie. A new picture of the dynamics of Mass. Bay has emerged in which wind events control buoyancy flow-through. The system is now in place for a variety of interdisciplinary studies of plankton patchiness and variability.

The theory of advective effects on biological dynamics is now ready for use with real ocean data. The analysis and theory provides information on parameter dependence in an NPZ system.

In a major accomplishment, a mesoscale induced nutrient injection mechanism for the euphotic zone due to eddy-eddy interactions has been used to explain the relatively high primary productivity of the Sargasso Sea implied by oxygen and other tracer data. This nutrient injection mechanism may be the dominant mode of nutrient transport in the open ocean.

IMPACT/APPLICATIONS

The important ESSE concept is that the evolution of 3D multivariate forecast variability and error can be efficiently described by a small number of adequate functions (e.g. error EOFs). The most energetic variability and error fields are expected to evolve in limited subspaces. In general, ESSE is useful for a wide range of applications, including nonlinear field and error forecasting, finding numerical instabilities, performing predictability studies, objective analyses, data-driven simulations, adaptive sampling and parameter estimation.

We now have a feasible methodology for biological field estimation and data assimilation, that is also applicable to satellite-derived data. An important implication is that the assimilation of ocean color data into physical-biological models should be concurrent with the assimilation of SST data. This is not only because the SST data can be used to fill in the gaps of the color data, but especially because the biological features need corresponding physical features to support them. Our methodology, in conjunction with the bio-optical modeling research being carried out in a related project, is also useful for assimilating ship-derived physical and biological data, and thus in ground-truthing satellite-based measurements.

Our improved understanding of the biological response to physical processes in fronts and mesoscale patches will provide useful to the basic research and applied research scientific communities.

Real-time regional forecasting research results are directly applicable to the design of ocean prediction and monitoring systems for: naval operations; research operations; the efficient environmental management of, and commercial operations within, a multi-use Exclusive Economic Zone; interdisciplinary global change research.

TRANSITIONS

Definitive results are passed to Harvard 6.2 research "Development of a Regional Coastal and Open Ocean Forecast System: Harvard Ocean Prediction System (HOPS)". These include, but are not limited to, the ESSE data assimilation methodology, improvements to the dynamical model upper ocean.

RELATED PROJECTS

This project is closely related to other Harvard projects, including: National Ocean Partnership Program in the development of the scientific and technical conceptual basis of a generally applicable Littoral Ocean Observing and Predictive System (LOOPS) with Johns Hopkins University (APL), MIT - AUV Lab., MIT - Sea Grant, MIT - Ocean Engineering, Naval Underwater Warfare Center, National Marine Fisheries Service, Raytheon, Tracor Applied Science, Univ. of California - Santa Barbara, Univ. of Massachusetts - Dartmouth; research towards the construction of an Advanced Fisheries Management and Information System (AFMIS) with UMass-Dartmouth (Prof. B. Rothschild); BIO-OPTICS research (Dr. Jeffrey Dusenberry); the Shelfbreak PRIMER and Harvard 6.2 research mentioned previously. In addition, important collaborations are ongoing with NRL Stennis (Dr. A. Warn-Varnas); U. Colorado (Dr. A. Moore); SIO (Dr. A. Miller); IMGA, Modena, Italy (Dr. N. Pinardi); Penn State Univ. Applied Research Lab. (Dr. S. Phoha) and the Naval Postgraduate School (Dr. Ching Sang Chiu).

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